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(71) Applicant *(for all designated States except US)*: BHP STEEL (JLA) PTY LTD [AU/AU]; 1 Castlereagh Street, Sydney, NSW 2000 (AU).

(71) Applicant *(for all designated States except FI US)*: ISHIKAWAJIMA-HARIMA HEAVY INDUSTRIES COMPANY LIMITED [JP/JP]; 2-1, Ohtemachi 2-chome, Chiyoda-ku, Tokyo (JP).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: MAHAPATRA, Rama, Ballav [AU/AU]; 6 Exmouth Place, Yarrawarrah, NSW 2233 (AU). FREEMAN, John [AU/AU]; 7 Lemana Place, Kahibah, NSW 2290 (AU). STREZOV, Lazar [AU/AU]; 7 Marin Street, Adamstown Heights, NSW 2289 (AU).

(74) Agent: GRIFFITH HACK & CO; 509 St Kilda Road, Melbourne, VIC 3004 (AU).

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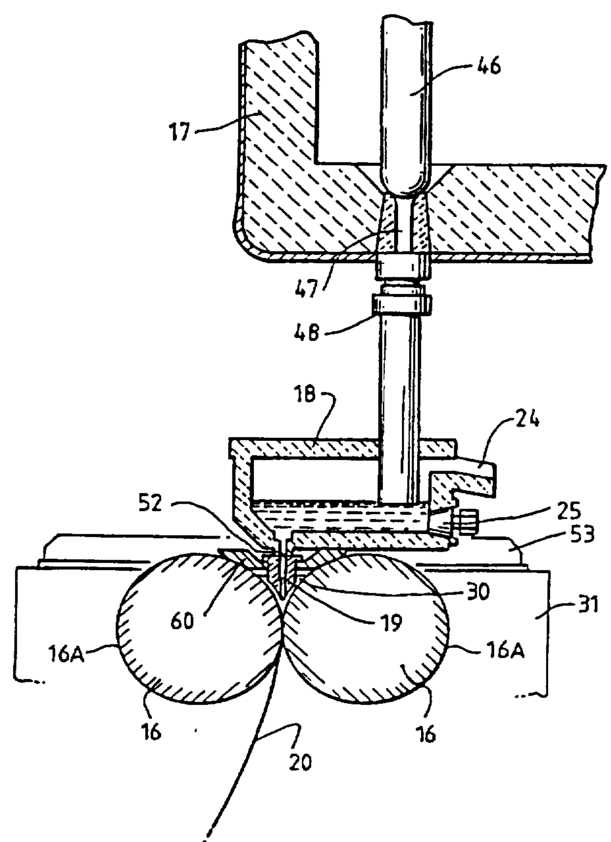
(54) Title: CASTING STAINLESS STEEL STRIP ON SURFACE WITH SPECIFIED ROUGHNESS

(57) Abstract

Method of continuously casting metal strip (20) from a casting pool of molten metal supported on chilled casting rolls (16) such that metal solidifies onto moving casting surfaces of the rolls. The metal is austenitic stainless steel containing chromium and nickel in a ratio $(Cr/Ni)_{eq}$ of less than 1.60 (preferably no greater than 1.55) and the casting surface of each roll has an Arithmetical Mean Roughness Value (R_a) of more than 2.5 microns (preferably in the range 2.5 to 15 microns).



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CASTING STAINLESS STEEL STRIP ON SURFACE WITH SPECIFIED ROUGHNESS

TECHNICAL FIELD

This invention relates to the casting of steel strip. It has particular but not exclusive application to continuous casting of stainless steel strip in a twin roll caster.

It is known to cast metal strip by continuous casting in a twin roll caster. Molten metal is introduced between a pair of contra-rotated horizontal casting rolls which are cooled so that metal shells solidify on the moving roll surfaces and are brought together at the nip between them to produce a solidified strip product delivered downwardly from the nip between the rolls. The term "nip" is used herein to refer to the general region at which the rolls are closest together. The molten metal may be poured from a ladle into a smaller vessel from which it flows through a metal delivery nozzle located above the nip so as to direct it into the nip between the rolls, so forming a casting pool of molten metal supported on the casting surfaces of the rolls immediately above the nip. This casting pool may be confined between side plates or dams held in sliding engagement with the ends of the rolls.

Twin roll casting has been applied with some success to non-ferrous metals which solidify rapidly on cooling, for example aluminium. Our Australian Patent No 631728 discloses a method and apparatus which enables continuous casting of ferrous strip within 0.5 mm to 5 mm and apparatus of this type has been developed to the stage where it is possible to consistently produce good quality mild steel strip. However there have been particular problems in casting austenitic stainless steel strip because of the marked tendency for such steel to suffer from cracking and repetitive surface depressions appearing as a surface defect generally known as "crocodile skin". We have undertaken extensive experimental work in which we have determined factors which make it possible consistently to cast austenitic stainless steel strip of good surface

quality without significant cracking defects.

In the ensuing description it will be necessary to refer to a quantitative measure of the smoothness of casting surfaces. One specific measure used in our experimental work and helpful in defining the scope of the present invention is the standard measure known as the Arithmetic Mean Roughness Value which is generally indicated by the symbol R_a. This value is defined as the arithmetical average value of all absolute distances of the roughness profile from the centre line of the profile within the measuring length l_m. The centre line of the profile is the line about which roughness is measured and is a line parallel to the general direction of the profile within the limits of the roughness-width cut-off such that sums of the areas contained between it and those parts of the profile which lie on either side of it are equal. The Arithmetic Mean Roughness Value may be defined as

$$R_a = \frac{1}{l_m} \int_{x=0}^{x=l_m} | y | \, dx$$

DISCLOSURE OF THE INVENTION

According to the invention there is provided a method of continuously casting metal strip of the kind in which a casting pool of molten metal is formed in contact with a moving casting surface such that metal solidifies from the pool onto the moving casting surface, wherein the metal is an austenitic stainless steel containing chromium and nickel in a ratio $(Cr/Ni)_{eq}$ of less than 1.60 and the casting surface has an Arithmetical Mean Roughness Value (R_a) of more than 2.5 microns. More particularly the Arithmetic Mean Roughness Value R_a of the casting surface may be in the range 2.5 to 15 microns. The surface of this texture may be produced by the machining of regular ridges in the surface.

Preferably the chromium to nickel ratio is no greater than 1.55.

More specifically the invention provides a method of continuously casting metal strip of the kind in which molten metal is introduced into the nip between a pair of casting rollers via metal delivery nozzle disposed above the nip to create a casting pool of molten metal supported on casting surfaces of the rolls immediately above the nip and the casting rolls are rotated to deliver a solidified metal strip downwardly from the nip, wherein the metal is an austenitic stainless steel containing chromium and nickel in a ratio (Cr/Ni) of less than 1.60 and the casting surfaces of the rolls have an Arithmetical Mean Roughness Value (R_a) of greater than 2.5 microns.

The casting surfaces of the rolls may have a texture of regular circumferential grooves with a texture depth in the range 10 microns to 60 microns and a groove pitch in the range 100 microns to 200 microns.

In an alternative embodiment, the roll may have a texture of regularly spaced projections, which may take the form of pyramids or cones with pitch spacing in the range 100 to 200 microns and depth in the range 10 to 60 microns.

It is preferred that the carbon, chromium and nickel contents of the steel be in the following ranges:

Carbon	-	0.04 - 0.06 % by weight
Chromium	-	17.5 - 19.5 % by weight
Nickel	-	8.0 - 10.0 % by weight.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the invention may be more fully explained its application to the production of stainless steel strip in a twin roll continuous caster will be explained with reference to the accompanying drawings in which:

Figure 1 is a plan view of a twin roll continuous strip caster which may be operated in accordance with the present invention;

Figure 2 is a side elevation of the strip caster shown in Figure 1;

Figure 3 is a vertical cross-section on the line

3-3 in Figure 1;

Figure 4 is a vertical cross section on the line 4-4 in Figure 1;

Figure 5 is a vertical cross-section on the line 5-5 of Figure 1;

Figure 6 illustrates the textured surface of a casting surface used in a series of trial casts; and

Figures 7 to 9 illustrate the results of the trial casts using steels of varying compositions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The illustrated caster comprises a main machine frame 11 which stands up from the factory floor 12. Frame 11 supports a casting roll carriage 13 which is horizontally movable between an assembly station 14 and a casting station 15. Carriage 13 carries a pair of parallel casting rolls 16 to which molten metal is supplied during a casting operation from a ladle 17 via a tundish 18 and delivery nozzle 19. Casting rolls 16 are water cooled so that shells solidify on the moving roll surfaces and are brought together at the nip between them to produce a solidified strip product 20 at the roll outlet. This product is fed to a standard coiler 21 and may subsequently be transferred to a second coiler 22. A receptacle 23 is mounted on the machine frame adjacent the casting station and molten metal can be diverted into this receptacle via an overflow spout 24 on the tundish or by withdrawal of an emergency plug 25 at one side of the tundish if there is a severe malformation of product or other severe malfunction during a casting operation.

Roll carriage 13 comprises a carriage frame 31 mounted by wheels 32 on rails 33 extending along part of the main machine frame 11 whereby roll carriage 13 as a whole is mounted for movement along the rails 33. Carriage frame 31 carries a pair of roll cradles 34 in which the rolls 16 are rotatably mounted. Roll cradles 34 are mounted on the carriage frame 31 by interengaging complementary slide members 35, 36 to allow the cradles to

be moved on the carriage under the influence of hydraulic cylinder units 37, 38 to adjust the nip between the casting rolls 16. The carriage is movable as a whole along the rails 33 by actuation of a double acting hydraulic piston and cylinder unit 39, connected between a drive bracket 40 on the roll carriage and the main machine frame so as to be actuable to move the roll carriage between the assembly station 14 and casting station 15 and vice versa.

Casting rolls 16 are contra rotated through drive shafts 41 from an electric motor and transmission mounted on carriage frame 31. Rolls 16 have copper peripheral walls formed with a series of longitudinally extending and circumferentially spaced water cooling passages supplied with cooling water through the roll ends from water supply ducts in the roll drive shafts 41 which are connected to water supply hoses 42 through rotary glands 43. The rolls may typically be about 500 mm diameter and up to 1300 mm long in order to produce 1300 mm wide strip product.

Ladle 17 is of entirely conventional construction and is supported via a yoke 45 on an overhead crane whence it can be brought into position from a hot metal receiving station. The ladle is fitted with a stopper rod 46 actuable by a servo cylinder to allow molten metal to flow from the ladle through an outlet nozzle 47 and refractory shroud 48 into tundish 18.

Tundish 18 is also of conventional construction. It is formed as a wide dish made of a refractory material such as magnesium oxide (MgO). One side of the tundish receives molten metal from the ladle and is provided with the aforesaid overflow 24 and emergency plug 25. The other side of the tundish is provided with a series of longitudinally spaced metal outlet openings 52. The lower part of the tundish carries mounting brackets 53 for mounting the tundish onto the roll carriage frame 31 and provided with apertures to receive indexing pegs 54 on the carriage frame so as to accurately locate the tundish.

Delivery nozzle 19 is formed as an elongate body

made of a refractory material such as alumina graphite. Its lower part is tapered so as to converge inwardly and downwardly so that it can project into the nip between casting rolls 16. It is provided with a mounting bracket 60 whereby to support it on the roll carriage frame and its upper part is formed with outwardly projecting side flanges 55 which locate on the mounting bracket.

Nozzle 19 may have a series of horizontally spaced generally vertically extending flow passages to produce a suitably low velocity discharge of metal throughout the width of the rolls and to deliver the molten metal into the nip between the rolls without direct impingement on the roll surfaces at which initial solidification occurs. Alternatively, the nozzle may have a single continuous slot outlet to deliver a low velocity curtain of molten metal directly into the nip between the rolls and/or it may be immersed in the molten metal pool.

The pool is confined at the ends of the rolls by a pair of side closure plates 56 which are held against stepped ends 57 of the rolls when the roll carriage is at the casting station. Side closure plates 56 are made of a strong refractory material, for example boron nitride, and have scalloped side edges 81 to match the curvature of the stepped ends 57 of the rolls. The side plates can be mounted in plate holders 82 which are movable at the casting station by actuation of a pair of hydraulic cylinder units 83 to bring the side plates into engagement with the stepped ends of the casting rolls to form end closures for the molten pool of metal formed on the casting rolls during a casting operation.

During a casting operation the ladle stopper rod 46 is actuated to allow molten metal to pour from the ladle to the tundish through the metal delivery nozzle whence it flows to the casting rolls. The clean head end of the strip product 20 is guided by actuation of an apron table 96 to the jaws of the coiler 21. Apron table 96 hangs from pivot mountings 97 on the main frame and can be swung

toward the coiler by actuation of an hydraulic cylinder unit 98 after the clean head end has been formed. Table 96 may operate against an upper strip guide flap 99 actuated by a piston and a cylinder unit 101 and the strip product 20 may be confined between a pair of vertical side rollers 102. After the head end has been guided in to the jaws of the coiler, the coiler is rotated to coil the strip product 20 and the apron table is allowed to swing back to its inoperative position where it simply hangs from the machine frame clear of the product which is taken directly onto the coiler 21. The resulting strip product 20 may be subsequently transferred to coiler 22 to produce a final coil for transport away from the caster.

It has been found in the operation of the above described apparatus that it is possible to consistently produce good austenitic stainless steel strip by careful adjustment of the steel chemistry in combination with the use of rolls having textured surfaces to minimise segregation through initial rapid cooling rates.

In austenitic stainless steel strip casting, solidification mode can play an important part in determining strip surface quality. Primary austenitic solidification mode which occurs when the Cr/Ni ratio is less than about 1.60 is not usually recommended as segregation is enhanced leading to an increase in cracking tendency. It has previously been thought necessary to ensure a Cr/Ni ratio within the range 1.7 to 1.9 in order to minimise cracks due to a reduction in segregation severity and to provide tortuous paths making crack propagation difficult. However our experimental work has shown that continuous strip casting with steel of this composition is very prone to produce strips with "crocodile skin" depressions and the depression severity may be so high as to cause cracking. Steel with Cr/Ni ratio less than 1.55 is most prone to segregation and can thus increase cracking. If solidification occurs on a smooth substrate initial heat transfer rates are low and the

solidification structure is coarse resulting in segregation and cracking. However we have determined that this tendency to segregation and cracking can be overcome by ensuring a high initial heat transfer rate and this can most readily be achieved by using a textured substrate, for example by the machining of ridges in the substrate surface.

Initial experimental work was carried out in a metal solidification test rig in which a 40 mm x 40 mm chilled block is plunged into a bath of molten steel at such a speed as to closely simulate the conditions at the casting surfaces of a twin roll caster. Steel solidifies onto the chilled block as it moves through the molten bath to produce a layer of solidified steel on the surface of the block. The thickness of this layer can be measured at points throughout its area to map variations in the solidification rate and therefore the effective rate of heat transfer at the various locations. It is thus possible to produce an overall solidification constant, generally indicated by the symbol K, as well as a map of individual values throughout the solidified strip. It is also possible to examine the micro structure of the strip surface to correlate changes in the solidification micro structure with the changes in the observed heat transfer values.

The nature of the experimental work and the results obtained will now be described.

EXPERIMENTAL CONDITIONS

Tests were conducted on three copper substrates with different surface characteristics; a smooth and a textured copper surface and a Cr coated (100 μm in thickness), ground surface. Texture was imparted to the copper block by machining longitudinal grooves and ridges with geometry shown schematically in Figure 6. Each of these blocks was instrumented with thermocouples to characterise the heat transfer rates prevailing during solidification. In order to maintain consistent casting

conditions throughout the experiments, variables such as melt superheat and block temperature were kept constant within reasonable limits. The melt temperature was aimed at about 1525°C corresponding to a superheat of 75°C. Argon gas introduced into the furnace was quite effective in preventing chemical interaction of the melt with the surrounding atmosphere. The melt chemistry was adjusted to achieve the desired $(Cr/Ni)_{eq}$ ratios, primarily through additions of Cr, Ni, C and N_2. The following expressions were used to determine Cr_{eq} and Ni_{eq}:

$$Cr_{eq} = Cr + 1.37\ Mo + 1.50\ Si + 2.0\ Nb + 3.0\ Ti \quad (1)$$

$$Ni_{eq} = Ni + 0.31\ Mn + 22.0\ C + 14.2\ N + Cu \quad (2)$$

A summary of the test conditions is contained in Table 1. The entire experimental program comprised approximately 45 tests with $(Cr/Ni)_{eq}$ ratios varying between 1.55 and 1.74. Salient features of various tests are summarised in Table 2.

Table 1: Experimental conditions

Substrate surface	Smooth copper Cr plated (ground) copper Textured copper (150μm pitch, 20μm depth)
Substrate cleaning procedure	Bristle brush and air blowing
Melt temperature	1525°C
Block temperature	125°C

Table 2: Details of the various tests

CONDITION	$(Cr/Ni)_{eq}$	MELT N_2	GAS ATM	TOTAL DIPS
1	1.56-1.71	0.047	Ar	9
2	1.58-1.71	0.037	Ar	9
3	1.57-1.61	<0.062	N_2	7
4	1.59	0.062	Ar	7
5	1.74	0.054-0.059	Ar Ar + He	15

RESULTS

Effect of $(Cr/Ni)_{eq}$ ratio on strip surface quality

Visual examination of the samples revealed that $(Cr/Ni)_{eq}$ ratio has a direct influence on the surface quality of the strip obtained with a textured substrate, however, no noticeable effect could be seen with the smooth substrates. Samples cast at varying $(Cr/Ni)_{eq}$ ratio, reveal a gradual progression from a severe crocodile skin type texture to a smooth surface texture with decreasing $(Cr/Ni)_{eq}$ ratio. The effect of $(Cr/Ni)_{eq}$ ratio on crocodile skin severity, shown in Figure 9, suggests that substantial improvements in strip surface quality can be achieved by keeping the $(Cr/Ni)_{eq}$ ratio less than 1.60.

Effect of $(Cr/Ni)_{eq}$ ratio on heat transfer during solidification

i) Textured substrate

Heat transfer rates from the strip surface to the substrate were determined from the measured substrate temperatures. Figure 7 shows the influence of melt $(Cr/Ni)_{eq}$ ratio on heat fluxes for a textured substrate. It can be seen that the profiles are characterised by an early peak in the heat flux followed by rapid reduction of this peak and with increasing time, heat flux approaches a constant value. Higher heat transfer rates (about 30 MW/m^2) encountered in the early stages of solidification can be attributed to the intimate contact.

The experimental program determined that the $(Cr/Ni)_{eq}$ ratio found to producing the best surface texture (on a textured substrate) is less than 1.60.

ii) Smooth substrate

Figure 8 reveals the influence of $(Cr/Ni)_{eq}$ ratio on heat transfer for a smooth substrate. It can be seen that the heat fluxes are relatively constant throughout solidification and most importantly, the magnitudes of the peak fluxes are much lower than those measured for a textured substrate (Figure 7). This finding is in agreement with the observed solidification structure which

is coarse at the surface. Although there are some variations in heat flux at different $(Cr/Ni)_{eq}$ ratios, there are no definite trends. However, with increasing time the heat fluxes approach similar values irrespective of $(Cr/Ni)_{eq}$. This apparent lack of dependence of heat transfer on $(Cr/Ni)_{eq}$ ratio with a smooth substrate is in agreement with the observations of strip surface texture which was not influenced by $(Cr/Ni)_{eq}$.

The experimental program demonstrated that the normal operating window for $(Cr/Ni)_{eq}$ ratios of 1.7-1.9 is not the optimum in terms of strip surface texture. Using a $(Cr/Ni)_{eq}$ ratio less than 1.60 produces better surface quality.

CLAIMS:

1. A method of continuously casting metal strip of the kind in which a casting pool of molten metal is formed in contact with a moving casting surface such that metal solidifies from the pool onto the moving casting surface, wherein the metal is an austenitic stainless steel containing chromium and nickel in a ratio $(Cr/Ni)_{eq}$ of less than 1.60 and the casting surface has an Arithmetical Mean Roughness Value (R_a) of more than 2.5 microns.

2. A method as claimed in claim 1, wherein the Arithmetical Mean Roughness Value (R_a) of the casting surface is in the range 2.5 to 15 microns.

3. A method as claimed in claim 2, wherein the casting surface has a texture of regular grooves and ridges.

4. A method as claimed in claim 3, wherein the texture depth is in the range 10 microns to 60 microns and the groove pitch is in the range 100 microns to 200 microns.

5. A method as claimed in claim 3, wherein the casting surface has a texture of regularly spaced discrete projections at a pitch spacing in the range 100 to 200 microns and a texture depth in the range 10 to 60 microns.

6. A method as claimed in any one of the preceding claims, wherein the chromium to nickel ratio is no greater than 1.55.

7. A method as claimed in any one of the preceding claims wherein the carbon, chromium and nickel contents of the steel are in the following ranges:

Carbon -	0.04 - 0.06 % by weight
Chromium -	17.5 - 19.5 % by weight
Nickel -	8.0 - 10.0 % by weight.

8. A method of continuously casting metal strip of the kind in which molten metal is introduced into the nip between a pair of casting rollers via metal delivery nozzle disposed above the nip to create a casting pool of molten metal supported on casting surfaces of the rolls immediately above the nip and the casting rolls are rotated to deliver a solidified metal strip downwardly from the

nip, wherein the metal is an austenitic stainless steel containing chromium and nickel in a ratio (Cr/Ni) of less than 1.60 and the casting surfaces of the rolls have an Arithmetical Mean Roughness Value (R_a) of greater than 2.5 microns.

9. A method as claimed in claim 8, wherein the Arithmetical Mean Roughness Value (R_a) of the casting surfaces of the rolls is in the range 2.5 to 15 microns.

10. A method as claimed in claim 9, wherein the casting surfaces of the rolls have a texture of regular circumferential grooves with a texture depth in the range 10 microns to 60 microns and a groove pitch in the range 100 microns to 200 microns.

11. A method as claimed in claim 9, wherein the rolls have a texture of regularly spaced discrete projections at a pitch spacing in the range 100 to 200 microns and a depth in the range 10 to 60 microns.

12. A method as claimed in any one of claims 8 to 11, wherein the chromium to nickel ratio is no greater than 1.55.

13. A method as claimed in any one of claims 8 to 12, wherein the carbon, chromium and nickel content of the steel are in the following ranges:

Carbon -	0.04 - 0.06 % by weight
Chromium -	17.5 - 19.5 % by weight
Nickel -	8.0 - 10.0 % by weight.

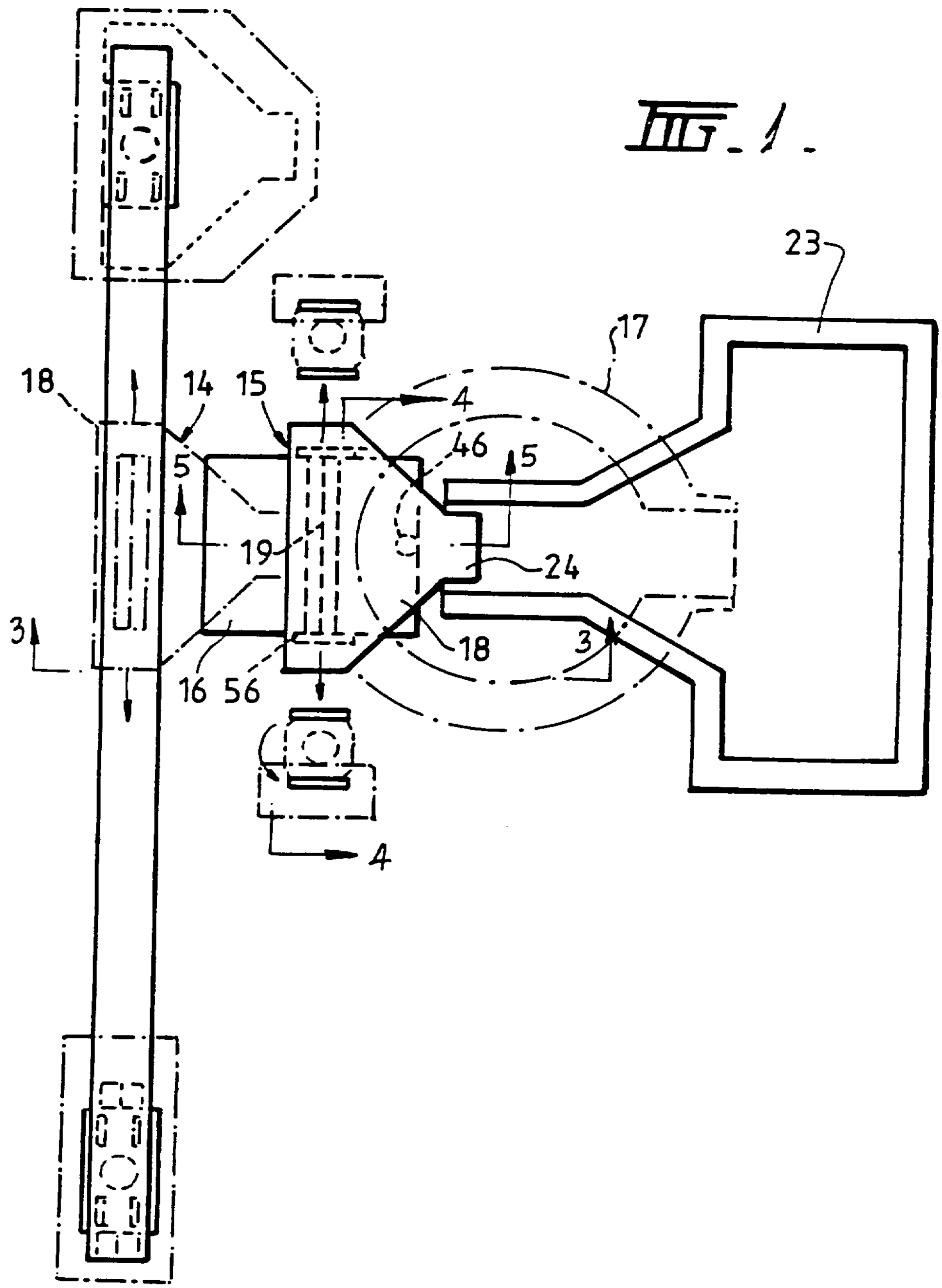

FIG. 1.

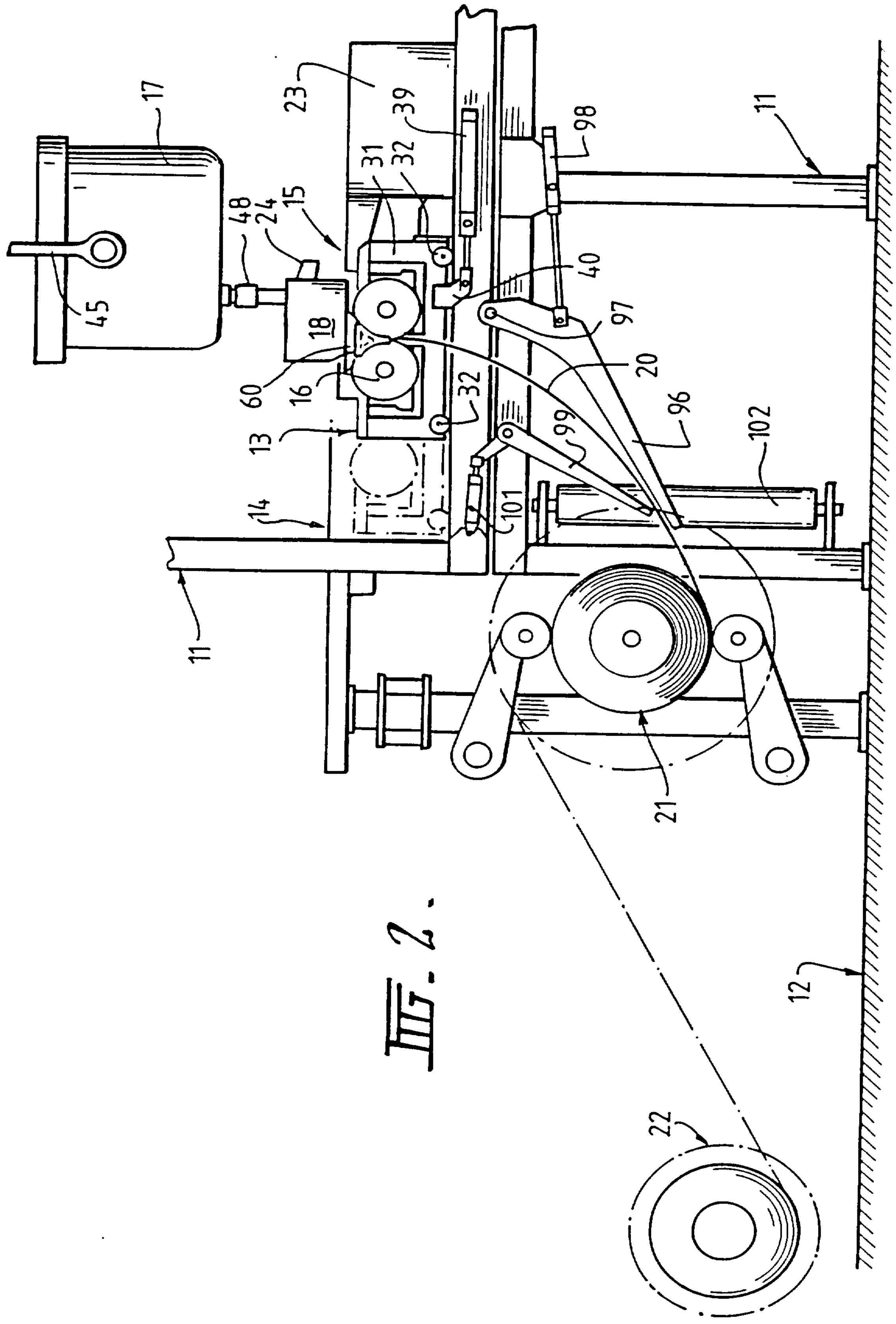
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FIG. 2.

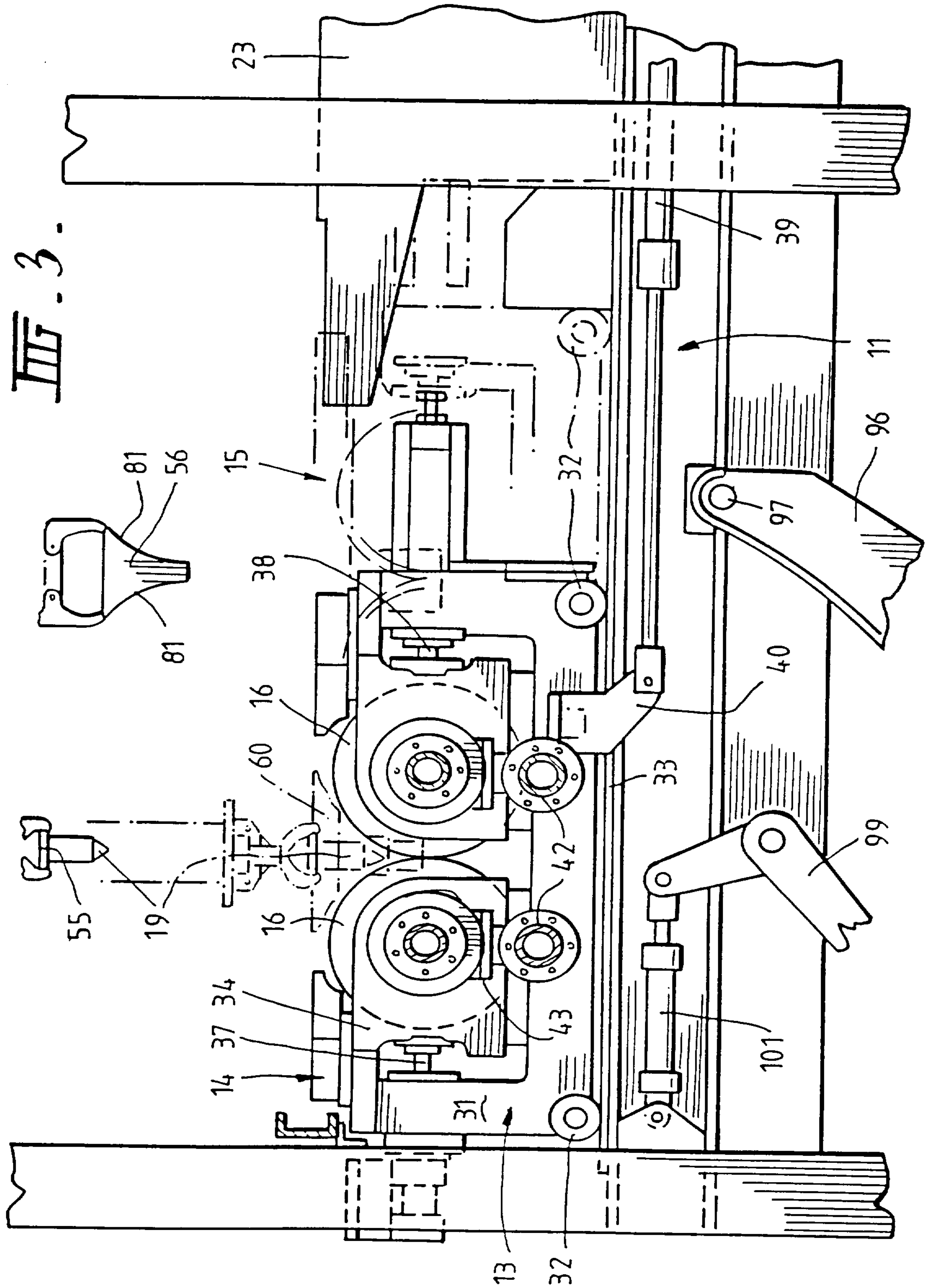
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FIG. 3.

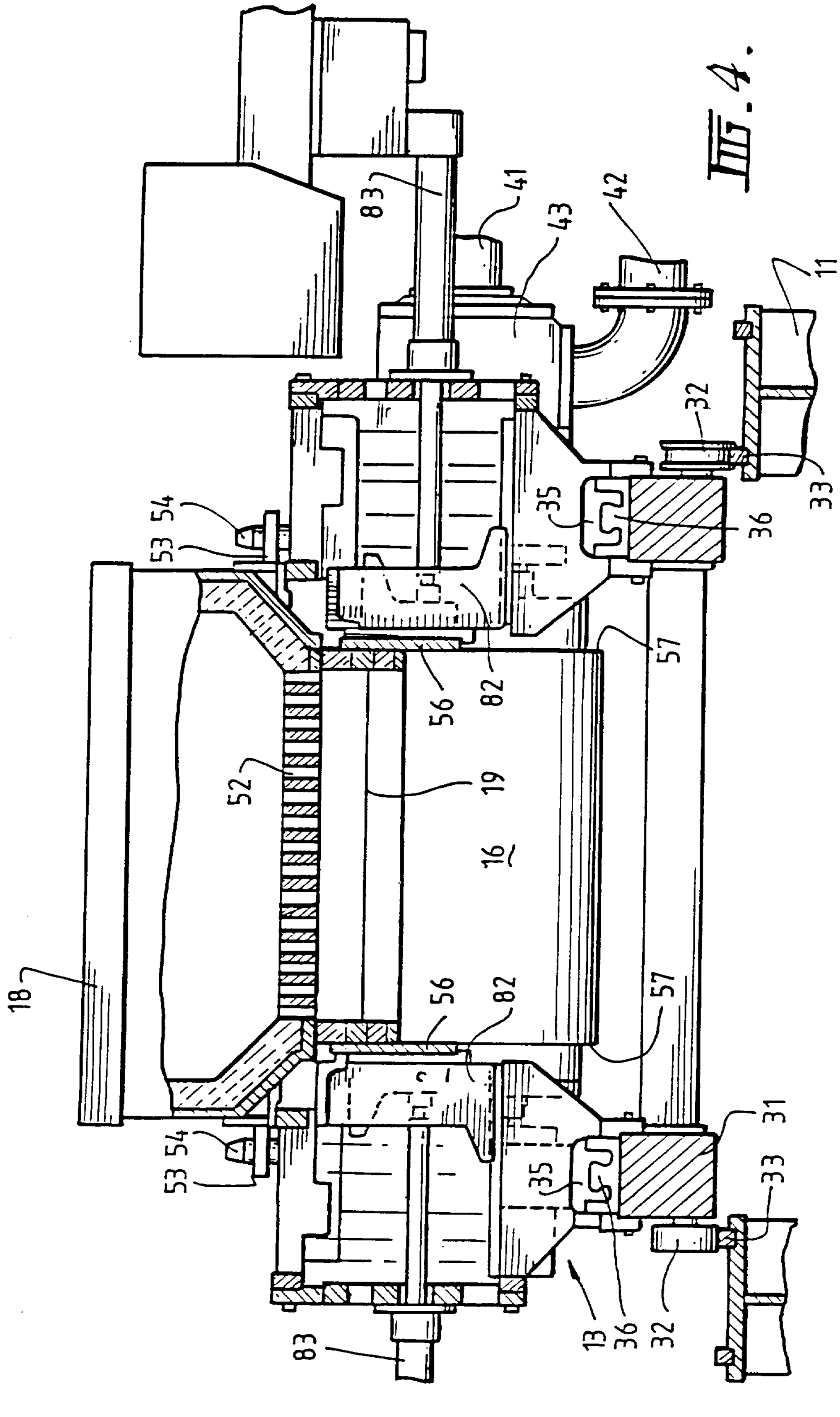


FIG. 4.

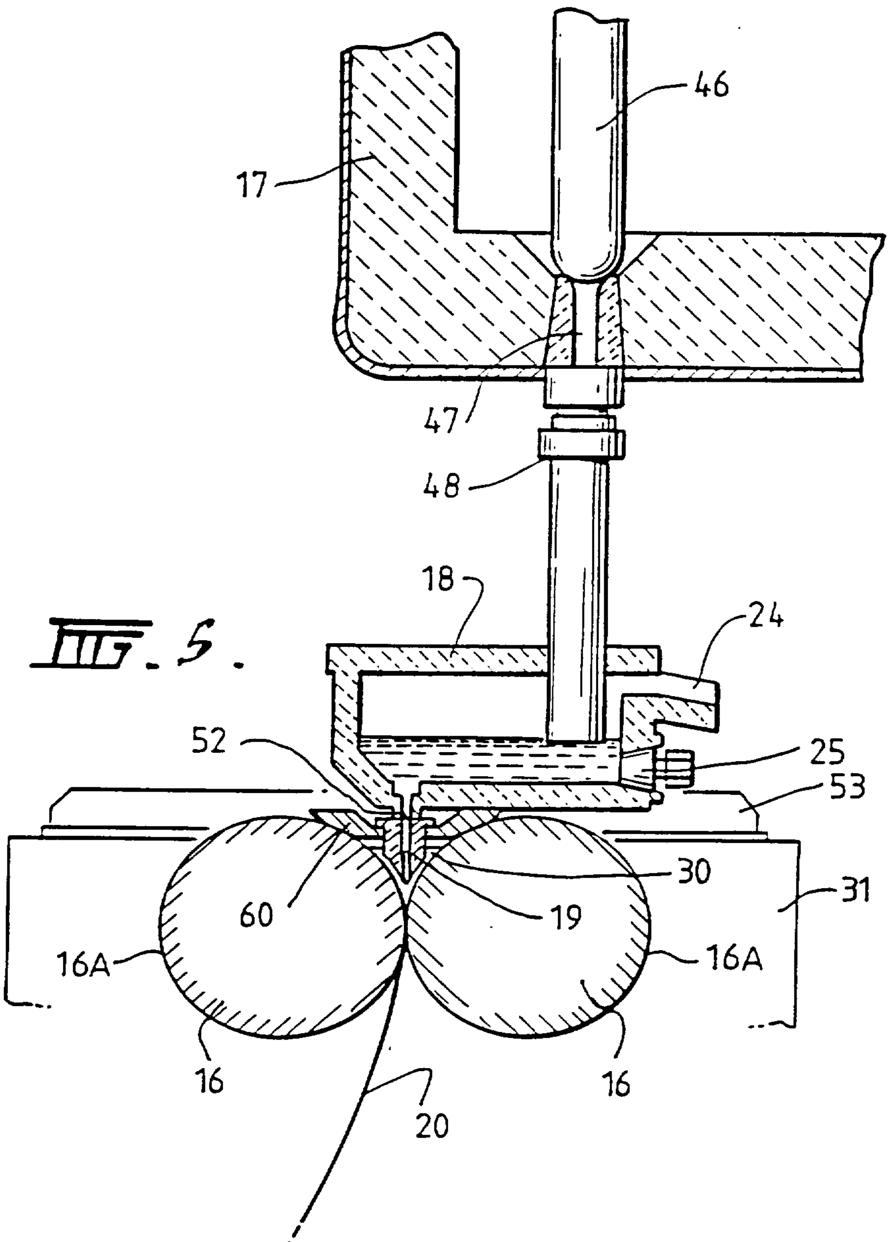


FIG. 5.

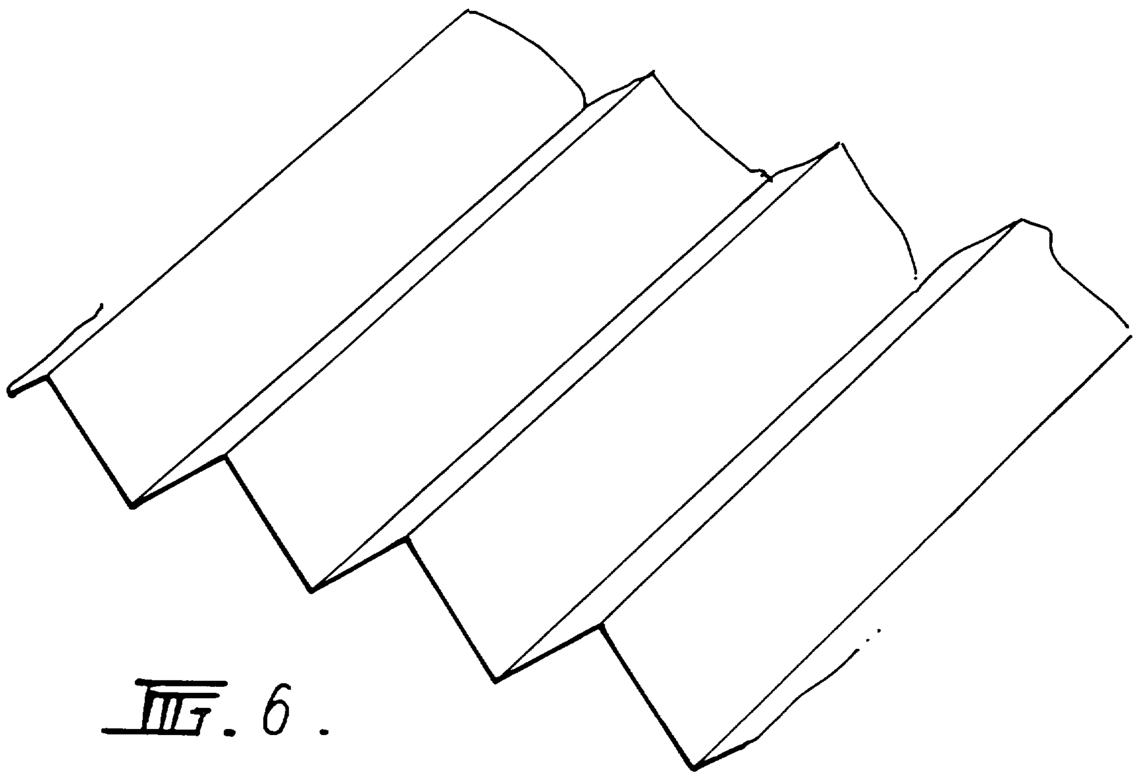


FIG. 6.

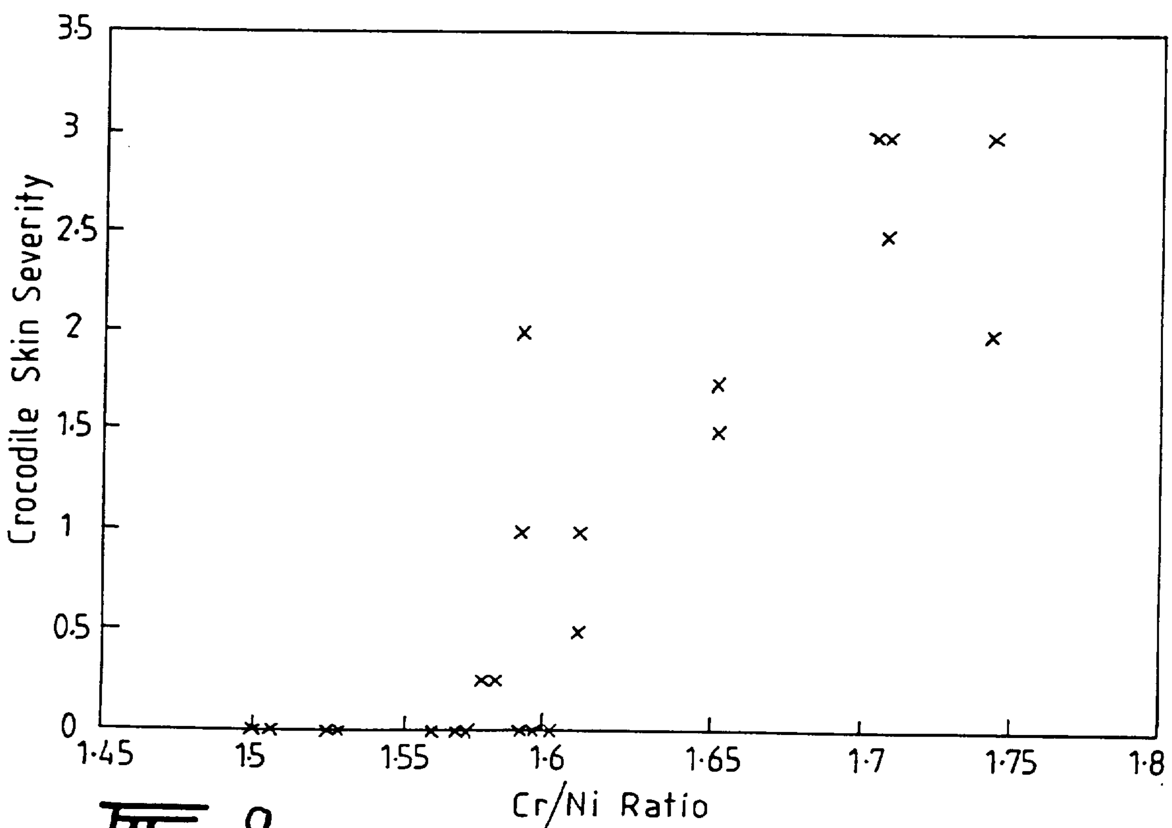
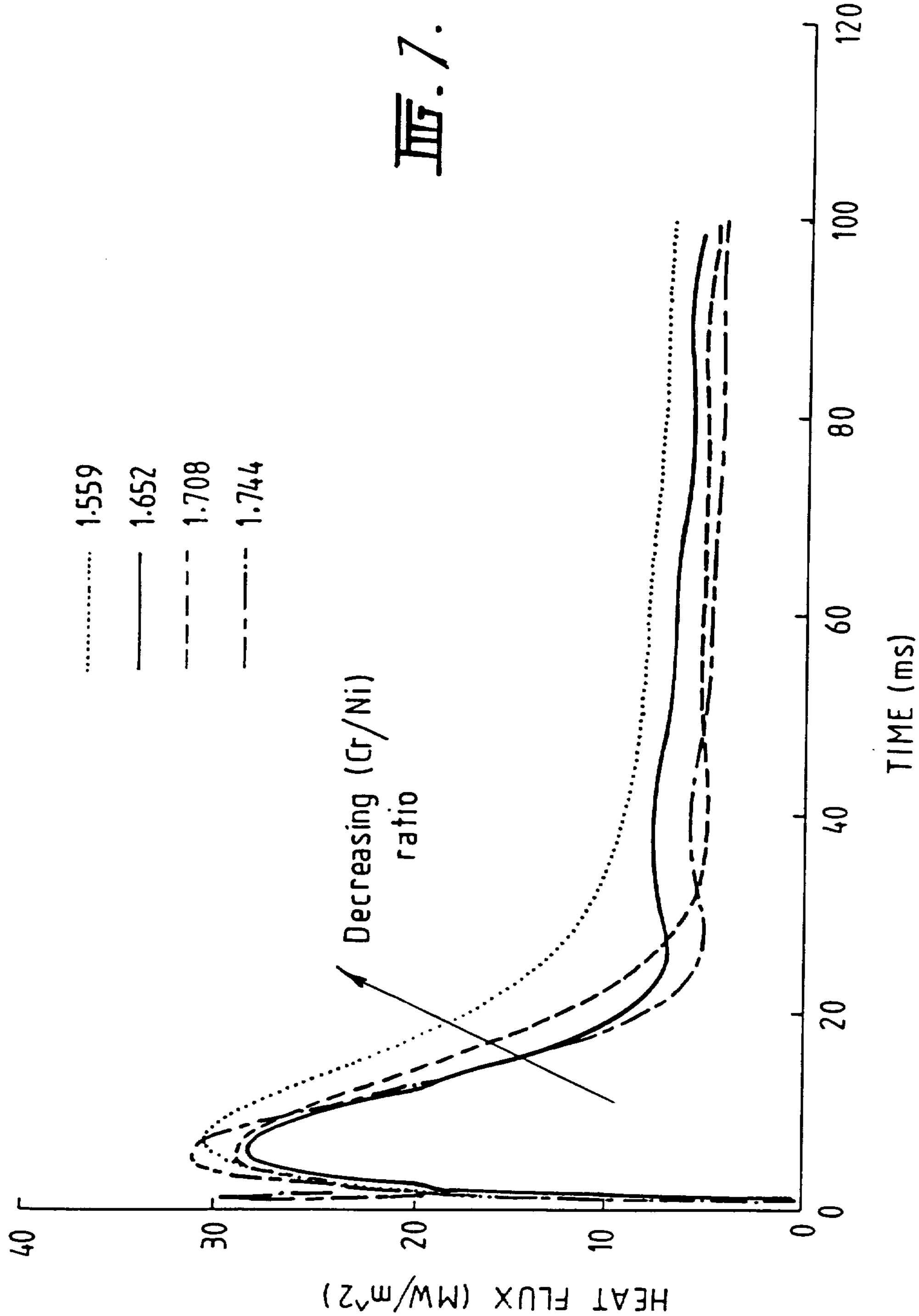

3.5
3
2.5
2
1.5
1
0.5
0
Crocodile Skin Severity
1.45
1.5
1.55
1.6
1.65
1.7
1.75
1.8
Cr/Ni Ratio

FIG. 9.


1.559
1.652
1.708
1.744
Decreasing (Cr/Ni) ratio
HEAT FLUX (MW/m^2)
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20
30
40
TIME (ms)
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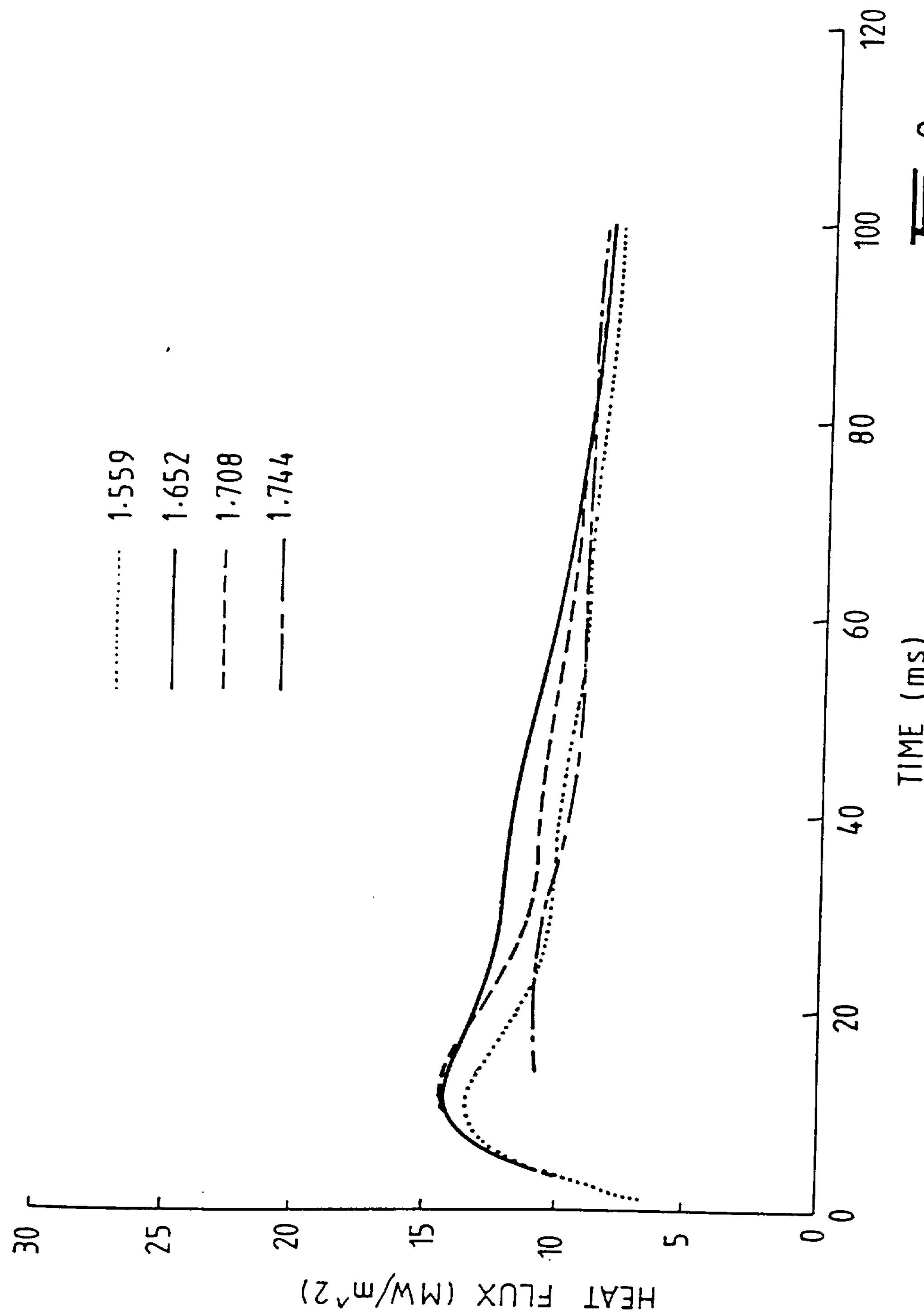
20
40
60
80
100
120

FIG. 7.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HEAT FLUX (MW/m^2)
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15
10
5
0
TIME (ms)
0
20
40
60
80
100
120

FIG. 8.

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.[6] B22D 11/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: B22D 11/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above.

Electronic data base consulted during the international search (name of data base, and where practicable, search terms used)
DERWENT, JAPIO: STEEL: and B22D 11/06

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	WO,A, 93/08941 (DAVY MCKEE [POOLE] LIMITED) 13 May 1993 (13.05.93) Abstract, figures 1-4.	
A	AU,A, 29929/92 (THYSSEN STAHL AKTIENGESELLSCHAFT, et al.) 17 June 1993 (17.06.93) Abstract, figs. 1,4	
A	US,A, 5082046 (BLIN) 21 January 1992 (21.01.92) Abstract, figs. 1-2	

☐ Further documents are listed in the continuation of Box C.

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Date of the actual completion of the international search	Date of mailing of the international search report
25 January 1995 (25.01.95)	7 Feb 1995 (7.2.95)

Name and mailing address of the ISA/AU

AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION
PO BOX 200
WODEN ACT 2606
AUSTRALIA

Facsimile No. 06 2853929

Authorized officer

Venkat Iyer

VENKAT IYER

Telephone No. (06) 2832144

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	93/08941	AU	287770/92				
AU	29929/92	DE	4241775	EP	546885	FR	2684904
		JP	5-329585				
US	5082046	AU	68272/90	BR	9006469	CN	1054550
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		ZA	9010214				

END OF ANNEX